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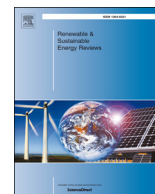
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The increasing importance of leading edge erosion and a review of existing protection solutions

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ABSTRACT

The offshore wind industry's pursuit of greater blade lengths and higher tip speeds, as well as a move to new markets with monsoonal climates, has caused leading edge erosion to progress from an issue that only affects a small number of turbines in the most extreme environments to a major problem that affects entire wind farms. Leading edge erosion results in reduced turbine efficiency that requires expensive repairs and tip speeds to be limited to protect blade edges. A review of the existing protection solutions is presented. The production and application of both gelcoats and flexible coatings relies heavily on manual procedures, leaving the coatings vulnerable to defects that can act as initiation points for erosion. Leading edge tapes are manufactured autonomously in a controlled environment and are consequently relatively free of defects. When applied effectively, the tapes possess very good erosion resistance. However, poor application can result in the formation of air pockets and wrinkles that reduce the adhesion of the bond, resulting in the tape debonding from the blade. Metallic erosion shields have been shown in accelerated rain erosion tests to possess a lifetime greater than that of an offshore wind turbine blade. However, differences in stiffness between the blade and the metallic shield introduces a risk of the shield detaching under loading and as a result, the reliance on the adhesive is high. Integrating a metallic erosion shield into the blade mould would remove an additional manufacturing process and alleviate any aerodynamic concerns caused by a profile step on the leading edge of the blade. A design that can account for the stiffness mismatch between an integrated metallic erosion shield and the blade may then reveal the solution to leading edge erosion.

1. Introduction

Blade leading edge erosion has become an important issue for the offshore wind industry. The performance of a wind turbine is largely dependent on the aerodynamic properties of its blades. Leading edge erosion is caused by raindrops, hailstones or other particles impacting the leading edge of the blade. This causes material to be removed from the blade surface, leaving a rough profile that degrades the aerodynamic performance and impacts the structural integrity of the blade. This can result in reduced turbine efficiency and expensive in-situ repairs, costing turbine operators through lost power generation and reduced availability. Leading edge erosion appears to be accelerated offshore due to a combination of a harsher environment and greater blade tip speeds, available offshore from reduced noise restrictions. As a result, blades can experience significant erosion within just a few years,

which considering their supposed 25-year service life, is a serious problem.

In 2013, Keegan [1] presented a review paper drawing together an amalgamation of anecdotal accounts, insights from experimental results and available field data, discussing the risks and mechanisms associated with leading edge erosion in wind turbine blades. Keegan [2] followed up the review paper with their doctoral thesis in 2014, where the damage mechanisms in protective solutions were examined through numerical and experimental methods. The research from Keegan has since become one of the most cited papers on leading edge erosion and helped to develop further understanding of the issue. However, the wind industry has continued its significant growth over the past five years and the landscape is now markedly different than in 2014. The aim of this paper is, therefore, to provide an up to date review of the prominence of leading edge erosion, discuss how the industry is

Abbreviations: AEP, annual energy production; DTV, damage threshold velocity; LCOE, levelised cost of energy; OEM, original equipment manufacturer; ORE Catapult, Offshore Renewable Energy Catapult; OWIH, Offshore Wind Innovation Hub

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Nomenclature

E_K	Kinetic energy of impinging particle
m	Mass of particle
v	Velocity of particle relative to blade surface

attempting to deal with the issue and critique the latest protection solutions.

2. The current wind energy climate

The wind industry has experienced rapid growth over the past two decades, playing an important role in the worldwide pursuit of clean and sustainable energy. Since the publication of Keegan's review paper, the amount of global cumulative wind capacity installed has grown from 319 GW to nearly 540 GW [3]. Offshore wind energy in particular is showing huge potential. Since 2013, the amount of cumulative offshore wind capacity has increased from 7 GW in 2013 to nearly 19 GW [3], as shown in Fig. 1.

This upward trend is only expected to accelerate over the next decade. Analysis conducted in 2017 from Bloomberg New Energy Finance [4] predicts a 16% compound annual growth rate with the cumulative offshore wind capacity reaching 115 GW by 2030. That would represent a six-fold increase on the capacity in 2017. Similarly, in a separate study, the International Renewable Energy Agency [5] estimate that the global offshore capacity will be at 100 GW by 2030. Clearly then, the offshore wind industry has experienced a significant level of growth since 2013, with this growth set to accelerate towards 2030.

The growth of the industry has been largely driven by increases in turbine size reducing the cost of offshore wind energy. Improvements in design, materials and manufacturing have enabled the production of ever greater blade lengths. Larger rotor diameters have two main benefits; the first is a greater swept area and therefore a greater power production, whilst the second is that it reduces the number of associated components that are required to be installed and maintained for a wind farm of a given size. Froese [6] reports that the industry has been increasing blade lengths by approximately 2 m every year for the last 10 years.

From 2013 to 2017, wind turbine capacity has doubled. In Europe, the average size of installed offshore wind turbines was 5.9 MW in 2017, a 26% increase on 2016 [4]. This is set to be surpassed further with the announcement of GE's 12 MW Haliade-X turbine, which has a rotor diameter of 220 m, blade lengths of 107 m and is expected to ship in 2021 [7]. Should the offshore wind industry continue its growth, it can easily be expected that 15 MW turbines will be commercialised in the 2030s [8].

Noise regulations have historically limited blade tip speeds for onshore wind turbines. Offshore, however, there are reduced regulations and offshore wind turbines have, therefore, been designed to take advantage of higher blade tip speeds. For a given power output, a higher tip speed reduces the torque load on the drivetrain, enabling the utilisation of lighter and cheaper drivetrains [9]. Dykes [10] found that a change in the maximum tip speed from 80 to 100 m/s could produce a 32% decrease in gearbox weight, which depending on the design approach would result in a reduction between 1% and 9% in the levelised cost of energy (LCOE) of the turbine. Naturally then, the offshore wind industry has pursued turbines with greater tip speeds. However, higher tip speeds increase the energy at which raindrops and hailstones impact the leading edge of a blade. Furthermore, the higher steady state wind speed offshore also increases the impact velocity of impinging water droplets. The average steady state wind speed offshore is approximately 14 m/s, whereas the steady state wind speed onshore is markedly less and varies between 6 and 9 m/s depending on location.

Another recent development has been the growth of the offshore wind industry in markets outside of Europe. In 2016, the first US offshore wind farm came online, China's offshore capacity increased by 64% to 1.6 GW, overtaking Denmark to become the third largest market, and Taiwan announced targets to have a capacity of 3 GW by 2025 [3]. BVG Associates [11] predict that the offshore wind capacity in Asia will increase from 1.7 GW installed at the end of 2016, to 11.3 GW by the end of 2022. To put that into perspective, the relatively established European market is anticipated by BVG Associates to reach 33.9 GW by 2022.

Asia, however, is home to severe monsoons with several countries receiving up to 80% of their annual rain in a single season, and therefore wind turbines can experience as much as three of four times the amount of rain that they may see in Northern Europe [12]. Fig. 2 presents rainfall data from NASA, clearly highlighting the additional average rainfall in the coastal areas of Asia.

The combination of an increased number of offshore turbine installations, larger turbines with higher tip speeds, and the recent growth of the industry in the demanding climates of Asia, have caused leading edge erosion to develop into a serious industry concern. In Keegan's review paper, many of the examples cited were anecdotal. However, recently erosion problems have become far more prominent and there now exists a far greater awareness around the issue. Lead Engineer for LM Wind Power's Materials Qualification and Technology Department, Haag [12] stated in 2015 that "ten or even five years ago, leading edge erosion mostly occurred in the most extreme environments, such as the west coast of Scotland where blades faced massive amounts of rain and wind. But, in the hunt for improved cost of energy through higher tip speeds, leading edge erosion is becoming much more dominant." This is supported by the Offshore Renewable Energy (ORE) Catapult as part of the Offshore Wind Innovation Hub (OWIH) [14], who, in collaboration with industry and academia, have developed a set of technology roadmaps to identify the priorities for the offshore wind sector. The consultation highlighted that leading edge erosion is the highest priority for blades for all operators and wind turbine manufacturers and that a solution to the issue has a 'high' potential to reduce the LCOE of offshore wind.

Furthermore, there has been several recent high profile cases of leading edge erosion. In March 2018, Siemens Gamesa had to perform "emergency" blade repair to 140 of the 175 turbines in the 630 MW London Array windfarm due to earlier than anticipated leading edge erosion [15]. This came a month after Siemens Gamesa was forced to remove 87 out of 111 turbines in a 400 MW farm in Anholt, Denmark [16]. In both cases, the turbines were 3.6 MW with a rotor diameter of 120 m and installed in 2013. The fact that what are now relatively small turbines experienced leading edge erosion on this scale after just five years highlights the seriousness of the issue facing the offshore wind

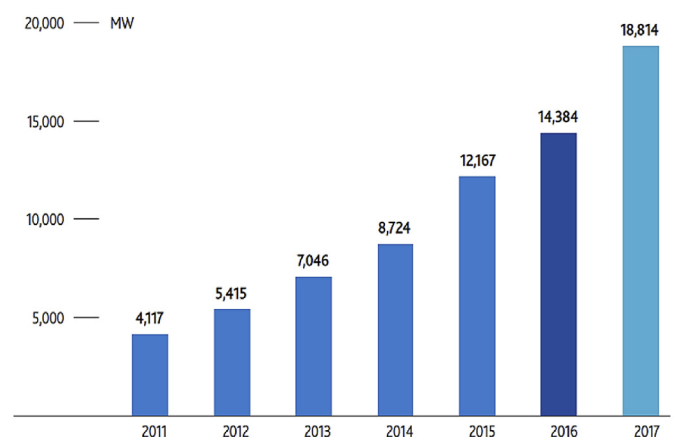


Fig. 1. Cumulative offshore wind capacity 2011–2017. Reprinted from Ref. [3] with permission.

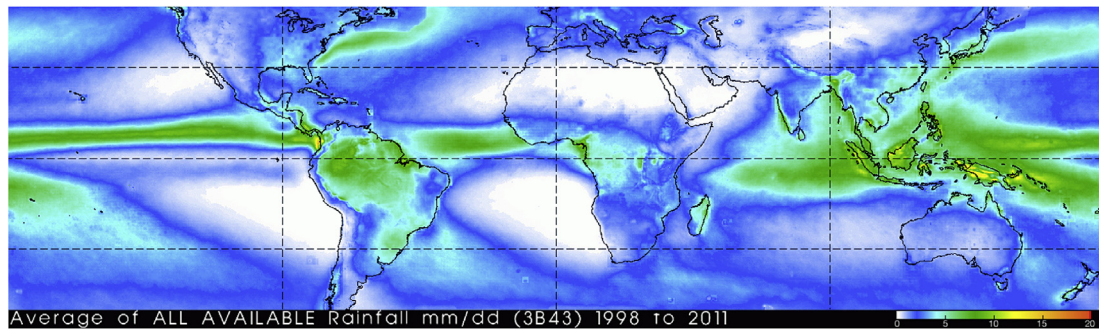


Fig. 2. Average rainfall between 1998 and 2011 across the globe. Reprinted from Ref. [13] with permission.

industry. The cost of the repairs is yet unknown and Siemens Gamesa plan to minimise lost revenue by fitting the blades with an aerodynamic upgrade to boost yield. Spare blades have also been fitted during the repairs. Erosion is now one of the primary reasons for downtime along with rotor imbalance, trailing edge disbands, lightning strike damage and edgewise vibration [17].

Keegan concluded in 2013 that the “frequency and severity of the problem is still uncertain”. The ORE Catapult OWIH consultation and the mass repairs experienced by Siemens Gamesa demonstrate that the severity of the problem is now understood. The frequency, however, is still unknown. The eroded 3.6 MW turbines were ironically 2013 turbines. Given the recent increase in turbine sizes and tip speeds, plus the ageing of existing turbines, it can be expected that the frequency of blade erosion cases will increase and begin to be understood over the next few years.

3. Why leading edge erosion is a problem

The recent developments in the offshore wind industry have led to research aiming to quantify the impact of leading edge erosion. This section examines the impact of the issue by means of discussing the recent research.

3.1. Effect on Annual Energy Production

To recognise the problem of leading edge erosion it is important to understand the impact that it has on the power production, and hence profitability, of a wind turbine. Leading edge erosion results in a rough blade profile that provokes an early laminar to turbulent transition. This increases the extent of transitional flow over the blade and reduces its aerodynamic properties [18].

The rate at which a wind turbine blade erodes is dependent on the tip speed, aerofoil shape and the environment in which it is situated. As a result, the level of leading edge erosion on a blade is typically defined qualitatively. This makes it difficult to effectively compare the erosion between blades and determine a timeline for the evolution of erosion. Quantifying the effect of erosion on the aerodynamic performance is therefore challenging and has been the focus of several research papers.

Gaudern [19] attempted to categorise the different stages of erosion by analysing inspection reports and photographs from Vestas turbines that had been operating for up to five years. The categories were then used to machine representative erosion patterns into blade leading edges and their aerodynamic performance investigated. All erosion configurations degraded the aerodynamic performance of the tested aerofoils by decreasing aerodynamic lift and increasing aerodynamic drag, with greater levels of erosion having a more severe impact and degrading the performance considerably. It was found that even just “minimal erosion” of small pin holes of missing paint distributed across the leading edge caused the lift and drag coefficients to decrease and increase by 4% and 49% respectively. Relatively severe erosion in the form of large coalesced eroded patches gave a 6% reduction and an

86% increase in the lift and drag coefficients respectively.

The impact of erosion can be better understood when considering its effect on the Annual Energy Production (AEP) of a turbine. Sareen [20] observed photographic records of wind turbine blades in operation and eroded blades undergoing repair and applied these to aerofoils in an attempt to analyse their effect on the AEP. An increase in drag of 6–500% was found across the various levels of erosion, and it was estimated that even a small amount of leading edge erosion can result in a reduction in the AEP of the turbine by 3–5%. The reduction in AEP approached 25% for the heavy erosion cases with pits, gouges and delaminations. Further analysis concluded that an 80% increase in drag, which was induced by a relatively small level of erosion, can result in a 5% reduction of the AEP.

In a similar study, Han [21] investigated the effect of various erosion conditions on the AEP of large wind turbines at high Reynolds number flows. The aerodynamic performance of NACA 64–618 aerofoils was analysed through CFD simulations and the AEP calculated by applying the data to the tip area of a 5 MW NREL reference wind turbine model. Leading edge erosion caused the lift and drag coefficients to decrease and increase by 53% and 314% respectively. The reduction in the aerodynamic performance was found to increase with the extent of leading edge erosion. It was concluded that the AEP losses ranged between 2 and 3.7% depending on the extent of damage at the leading edge.

Whilst both studies resulted in a drop in the AEP, there are dissimilarities in the value produced with the worst case scenario presented by Sareen at 25% compared with 3.7% presented by Han. The discrepancy may be down to differences in Reynolds numbers used by the two authors; Sareen used Reynolds numbers ranging between 1 and 1.85×10^6 , whilst Han explored the turbine at rated power and used a value of 6×10^6 . Research from Maniaci [22] confirms that a turbine at rated power experiences a smaller reduction in AEP due to the same level of erosion. Maniaci found that a turbine operating at rated wind speed experiences a drop in AEP of approximately 1.7%, whilst a turbine operating at a wind speed of 5 m/s has a 4.5% drop in AEP. However, the extent of blade roughness used by Maniaci is unclear.

Furthermore, the authors differed in their use of erosion patterns. Both used observations from eroded turbines to develop their model. However, it could be argued that the pattern used by Sareen is more representative as it accounts for a combination of pits, gouges and delamination, and distributes them randomly, as opposed to the pattern used by Han, who varies the erosion width and depth depending on the severity of erosion.

The disagreement in the results of Sareen and Han underlines the challenges in defining erosion and quantifying its impact. This was reflected by Langel [23], who attempted to help quantify the effect of leading edge erosion on wind turbine performance and developed a surface roughness model. As expected, the study found that a greater roughness increased drag and reduced lift. However, Langel faced challenges quantifying the roughness, instead only serving to allow the comparison of different aerofoils sensitivity to roughness.

The above studies all attempt to reproduce erosion patterns and therefore there is debate around how accurate they are. A campaign by ORE Catapult [24] aimed to provide more representative results by measuring the effect of erosion on the AEP of operating offshore wind turbines. It was found that an uplift in AEP between 1.5 and 2% can be achieved following the repair of moderate erosion. Whilst not as large as the AEP losses presented by Sareen, the losses are still significant.

An important metric to wind energy companies is the profitability impact of a reduction in the AEP. Wisser calculated that the loss in AEP from blade leading edge erosion accounts for a loss in productivity worth between €56 million and €75 million a year across the European offshore wind energy sector [25].

3.2. . Maintenance & repair

To recover lost aerodynamic performance, it is important to repair the leading edge of a damaged blade. Offshore wind turbines are sold by Original Equipment Manufacturers (OEMs) with warranty periods of typically five years [26], during which the OEM is responsible for any required repairs. At the end of the warranty period, it becomes the responsibility of the wind farm operator to maintain their assets.

Bladen's *Blade Inspection Instruction Manual* [27] provides a guideline for inspecting and categorising blade damage that can be used for determining when erosion becomes necessary to repair. The manual identifies that leading edge erosion penetrating down to the blade laminate, or a damaged leading edge protection solution, should be repaired within six months. When the damage breaks through the first layer of the laminate, repairs should be conducted within three months and only when the damage has broken through the entire laminate thickness should repairs be conducted immediately.

Furthermore, it is speculated that some OEMs do not repair the leading edge until the end of the warranty [28]. This would infer that erosion is left to develop for significant periods of time, reducing the power production and potentially causing extensive damage to the blade. This goes against industry advice that to reduce downtime and costs, repairs should be performed early [29]. Testing from WTG Offshore [30] endorses an early intervention strategy in managing leading edge erosion. Rain erosion tests were performed on protective coatings applied to undamaged samples, and on protective coatings applied to previously eroded and then repaired samples. It was found that coatings applied over a damaged and repaired sample eroded at a far quicker rate and decreased the durability of the coating by nearly 70%. If, as suggested, erosion is being left until the end of the warranty period, then any repair patch can be expected to last for a significantly shorter time period than if it had been repaired as soon as erosion was detected. This would infer that wind farm owners are likely to have to regularly perform repairs once the warranty period ends and they become responsible for the maintenance of the turbine.

Performing the repairs however, can lead to a significant period of downtime as the operator waits for a suitable wind and weather window and incurs substantial costs in technicians, equipment and vessel hire. Insight from Kay [31] states that operators will then only perform repairs when the loss in AEP outweighs the cost of repair. Determining the point at which this occurs is challenging due to the difficulties in quantifying the progression of leading edge erosion.

Turbine operators try to schedule remedial action during periods of low wind and aim to avoid unscheduled maintenance. Safety concerns also limit repairs to wind speeds less than 12 m/s. GL Garrad Hassan [32] estimates that an operator of a 500 MW offshore wind farm spends between £2 million and £8 million per year on turbine maintenance alone. Add to this the cost of turbine downtime and it becomes clear the significant cost associated with performing maintenance on wind turbine blades.

When offshore repairs are conducted, they are generally carried out in situ, with a technician accessing the damaged part area harnessed by rope. Cherry pickers and blade access modules are also utilised for

repairs. Whilst access for repairs is cumbersome, environmental conditions pose a larger issue [33]. Temperature, humidity and UV radiation can all affect the performance and curing of coating systems, resins and fabrics used in the repair patches, and repair patch manufacturers recommend only applying the patches under certain conditions. However, weather window limitations mean that achieving the correct conditions offshore is not always possible. The quality of the repair is also highly dependent on operator skill and experience. As a result, blade repairs can often be unsatisfactory, and lower quality than the repair is designed to be. Consequently, reports indicate that some repair patches fail within six to 12 months and the majority seldom last longer than one to two years [34].

The high cost of scheduling full turbine inspections results in many windfarm operators only inspecting the turbine every two to three years and therefore repair failures often go unnoticed until the next inspection period [34]. In addition to the cost of AEP losses, Wisser also estimates that blade leading edge erosion costs the European offshore wind sector €56 million a year in inspection and repair costs [25]. Furthermore, it is also estimated that the cost of the repairs combined with the lost power production could cost up to £1.3 million per turbine over its lifetime [35].

Any protection solution that can extend the lifetime of the turbine and reduce the frequency of repairs has the potential to greatly reduce the operation and maintenance cost of offshore wind turbines and hence have a noteworthy impact on the LCOE of offshore wind.

3.3. . Limiting the tip speed of the turbines

A higher tip speed ratio allows the use of cheaper and lighter gearboxes, and hence reduces the LCOE of the turbine. High tip speeds alter the severity of an impact of a raindrop, hailstone or another particle impinging on a blade surface quantified by the kinetic energy, E_K , of the particle:

$$E_K = \frac{1}{2}mv^2 \quad (1)$$

where m is the mass of the particle and v is the velocity of the particle relative to the blade surface, which is effectively equivalent to the blade speed. This shows that the blade speed is therefore the most influential factor in defining the severity of the impact of the blade with a raindrop, hailstone or particle [36].

Siddons [37] explored the effect of impact velocity and rainfall rate on the mass loss of unprotected composite samples. The investigation found that whilst the rainfall rate did influence the mass loss of the samples, the impact from an increase in velocity was far greater, leading Siddons to conclude that the velocity of a wind turbine plays a greater role in the erosion of the turbine than the rainfall conditions it is situated in. The raindrop size used in the investigations by Siddons was fixed at 2.5 mm. Fig. 3 shows that the rainfall rate and droplet size are not independent and a variation in the rainfall rate influences the raindrop size and hence its mass. This was not accounted for and so it can be determined from Fig. 3 that a greater rain flow rate is likely to have a greater effect on the erosion rate than Siddons suggests. Nevertheless, rain erosion tests from Thiruvengadam [38] also found that rain erosion on each individual material is largely dictated by the rotational impact velocity, identifying the eroding effect to be proportional to the relative velocity of the blade to the 5th power. The material response to different impact velocities in non-elastic materials then also defines the level of erosion that occurs.

Keegan explored the damage threshold velocity (DTV) of epoxies with various values of fracture toughness; where the DTV is defined as the lowest impact velocity at which damage is observed. The analysis found that for droplet sizes with a diameter greater than 2 mm, the DTV could be as low as 50 m/s for low fracture toughness values, and even for higher toughness values, the DTV is still lower than the current 100 m/s tip speed limit. An examination of Fig. 3 in combination with

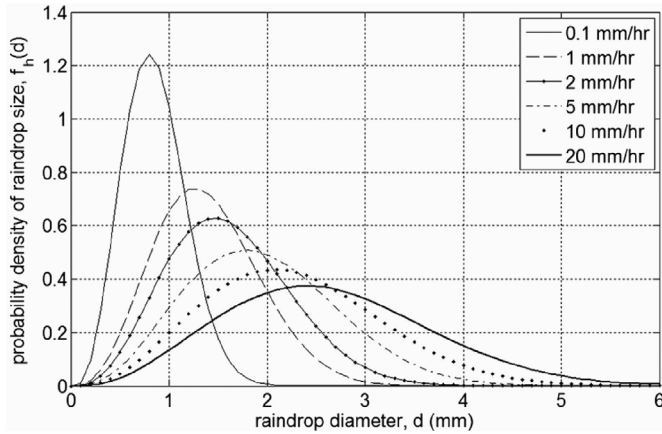


Fig. 3. Probability distribution of raindrop size for various rainfall rates. Reprinted from Ref. [39] with permission from Elsevier.

the average rainfall across the globe (Fig. 2) shows that raindrop diameters greater than 2 mm occur with increasing frequency in areas with high rainfall rates, such as the coastal areas of Asia. This implies that the DTV in these regions could be far lower than current tip speeds.

Selecting the limiting tip speed of the turbine is a compromise between minimising gearbox cost and reducing the rate at which the blades erode. Currently, leading edge erosion limits tip speeds to around 100 m/s [40].

Bech [41] explores the idea of introducing an “erosion safe mode”, which involves reducing the tip speed of the turbine during extreme precipitation events. During these events, some power production would be sacrificed to reduce the impact of particles on the blade, extending their lifetimes. This would increase the AEP in the long-term. Whilst this idea shows some promise, a solution to leading edge erosion would allow turbines to achieve higher tip speeds without having to engage a “safe mode”.

3.4. . Summary of the problem of leading edge erosion

The costs associated with lost AEP and maintenance operations illustrates the detrimental impact of leading edge erosion, and the need for erosion mitigation strategies. Methods that can delay the onset of leading edge erosion or eliminate it all together have the potential to make significant cost savings to the industry by:

- Minimising the aerodynamic degradation of the blade profile, minimising lost AEP,
- Reducing the frequency of maintenance operations and the associated risks of unsatisfactory blade repairs,
- Removing the cap on current tip speeds, allowing the use of lower cost drivetrain solutions.

4. Rain droplet phenomena

As the issue of leading edge erosion has developed prominence within the industry, greater emphasis has been placed on the development of protective solutions that can increase the lifetime of the turbine. To understand the relative merits and flaws of the various systems, it is first important to understand the phenomena that occur when a rain droplet impacts a surface.

The progression of erosion can be broken down into three stages [42]. The first stage is the incubation period, where the surface is virtually unaffected and there is no observable mass loss. In the second stage, mass loss begins and accelerates, before the rate of degradation reduces in the final stage. In this stage the resulting surface roughness is severe, and liquid accumulates in the surface damage, which reduces the impact damage of the oncoming droplets.

When a water droplet impinges on a surface of a material at a normal angle, a compressional shock wave is generated and propagated through the material (Fig. 4a). As the contact area between the droplet and the material increases, shear waves are created that propagate through the material and away from the impact location [43]. How these waves travel through the material is largely dependent on the material's acoustic impedance through the thickness [44]. Impedance is linked to the stiffness of the material and hence also hardness. A material with a higher impedance will absorb a greater proportion of the wave energy than a material with a lower impedance, which will transmit a greater proportion of the energy. A high impedance protection solution therefore moderates the stresses transmitted from the droplet to the protection system and the blade substrate [45]. However, the energy absorbed by the material can cause changes to the material itself allowing cracks and other forms of erosion damage to occur. This damage then acts as a nucleation point for further damage [46].

A compressed liquid wave front travelling upwards in the droplet is also created upon impingement [43]. Once the wave front spreads past the contact periphery between the droplet and surface (Fig. 4b), the droplet collapses in on itself and lateral jets, with a speed up to 40 times the original impact speed [47], spread radially outwards from the impact location over the surface. The proportion of the initial impact energy that is reflected into the droplet or transferred to the material is dependent on the surface hardness. A hard material will reflect a greater proportion of the initial impact energy back into the droplet causing a large amount of jetting across the surface. Conversely, a soft material will deform upon impact to absorb the impact energy, reducing the proportion of energy reflected into the droplet and therefore reducing the surface splashing [48]. This leads to the formation of pits on the surface. The level of surface deformation is dependent on the short and long term recovery of the material, which is defined by the elasticity and viscoelasticity of the material, respectively [49].

A smooth surface restricts the damage mechanisms to stress wave propagation and direct deformation [50]. However, once a material becomes rough, it becomes vulnerable to the lateral jetting process. When the lateral jets encounter any surface asperities, large shear stresses are induced in the surface that can further roughen and damage the material [42].

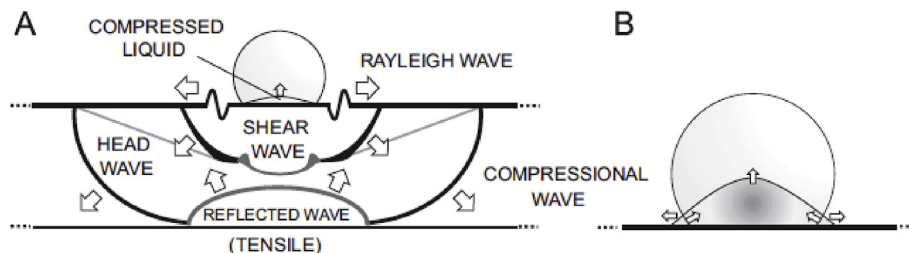


Fig. 4. a) Shock wave propagation occurring upon raindrop impact on a solid surface, b) compressed liquid wave front spreading past the contact periphery. Reprinted from Ref. [43] with permission from Elsevier.

5. Protection solutions

There are several protection solutions available to the industry that can increase the lifetime of the turbine by mitigating leading edge erosion. However, given the impact of the issue, selecting the right leading edge protection is now more important than ever before [51]. This section provides a description of the various systems and disseminates their benefits and weaknesses.

5.1. . Coatings

Protective coatings, typically consisting of impact resistive materials, can be applied to the surface of the blade. The coatings can be applied in-mould or post-mould.

The in-mould technique applies a coating layer (**gelcoat**) of similar material to the matrix material, typically an epoxy, polyester or polyurethane, in the mould during the manufacturing process (Fig. 5). The gelcoat is the first layer in the mould and the fibres are laid on top. The fibres are then infused with resin and the whole system cured, forming a chemical bond between the gelcoat and the matrix material. When the blade is removed from the mould, the gelcoat becomes the external layer.

The in-mould technique has the advantage of applying a protection coating to the blade surface without an additional manufacturing step. To ensure satisfactory mechanical performance and durability, optimum adhesion between the composite laminate and gelcoat is required [53].

In the post-mould approach, **flexible coatings**, such as polyurethane, are applied after the manufacturing process to the blade surface, typically applied by rollers or spraying [54]. Fig. 6 shows the different application procedures. Application is multi-layered with a filler layer applied to the blade to provide a smooth surface for the application of the flexible coating. Some manufacturers include a primer layer between the filler and the coating to further aid adhesion [45].

Gelcoats are typically brittle and have a high acoustic impedance. Conversely, flexible coatings are typically more ductile and have a low impedance. Flexible coatings exhibit high strain to failure rates and reduce the stress at the impact surface. This effectively dampens the oscillating stress waves, ensuring that the energy of the impact is dissipated quickly.

The different properties of gelcoats and flexible coatings causes them to exhibit different responses under particle impingement. Keegan's thesis developed finite element models to identify the damage mechanisms in gelcoats and flexible coatings, both in isolation and when applied to a blade surface. The dominant form of damage for gelcoats was found to be surface degradation and erosion. The

modelling showed that the impingement of a rain droplet generated compressional stresses that were propagated through the gelcoat. The stress values produced, however, were unlikely to cause immediate plasticity. In fact, the most damaging process was found to be the lateral jetting where the droplet spreads across the surface at high velocity as a result of a large proportion of the impact energy being reflected into the droplet. Consequently, damage was limited to the surface or near surface of the coating, and naturally there was no change when the gelcoat was modelled with the composite. Keegan found that flexible coatings exhibited significant geometric deformation that allowed a smoother impact response and reduced surface damage. Instead the inclusion of the composite substrate found that the most damaging mechanism was subsurface degradation and weakening of the bond between the coating and substrate. Keegan concluded that care must therefore be taken to ensure that the bond is robust and long lasting to avoid debonding, and thus exploit the reduced surface damage protection offered by the coating. Keegan proposes that this debonding occurs due to the large difference in flexibility between the coating and the substrate. Conversely, delamination is unlikely to occur for the gelcoat due to the inherent bonded nature of the gelcoat to the resin matrix generated during the in-mould cure.

Keegan's work agreed with earlier work from Field [55] who also highlighted the risk of debonding in flexible coatings. The study identified that differences in flexibility resulted in intrinsic stresses in the system, often compressive in the coating and tensile in the substrate. These stresses increase the risk of debonding and can damage the substrate.

More recent research from Cortés [45] evaluated the rain erosion resistance of an epoxy gelcoat and an elastomeric flexible coating applied over two layers of biaxial glass fibre in a whirling arm erosion test. In agreement with Keegan, the flexible coating exhibited minimal surface damage, whilst the gelcoats experienced surface damage in the form of pits and cracks. Severe delamination in the composite substrate subsequently occurred in these damaged areas once the gelcoat had been eroded. The test concludes that flexible coatings offer better erosion protection than the more rigid gelcoats.

A review of coating life models conducted by Slot [56] determined that surface fatigue best describes the erosive wear and failure of coatings. Coatings, therefore, need to be optimised to reduce surface fatigue wear, with Slot recommending that coating development should focus on reducing the impact pressure from the rain drop and concludes that coatings with a lower modulus of elasticity should be developed. Flexible coatings have a lower modulus of elasticity than gelcoats and therefore the review agrees with the results of the rain erosion tests performed by Cortés, where flexible coatings significantly outperformed gelcoats.

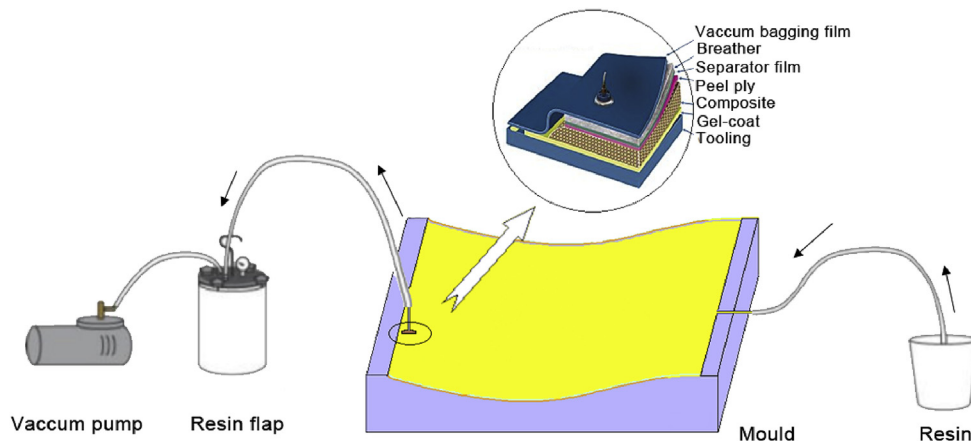


Fig. 5. Applying the gelcoat in the in-mould technique. Reprinted from Ref. [52] with permission.

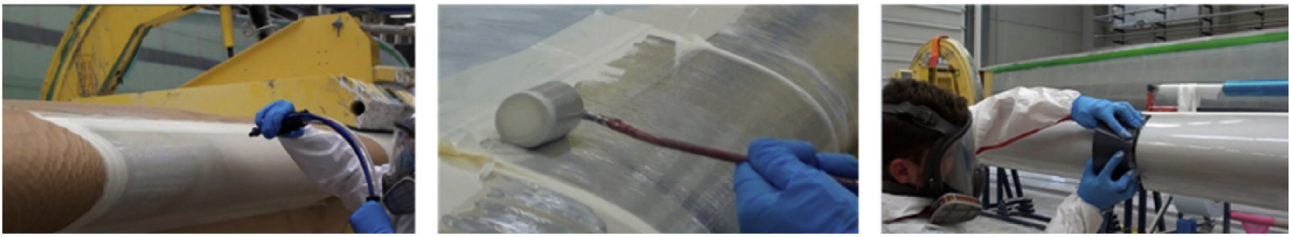


Fig. 6. Post-mould application methods, from left to right: spray, roller, trowel. Reprinted from Ref. [45] with permission.

5.1.1. The effect of defects

The method for applying a coating is highly labour intensive and not automated. A coating must be accurately mixed, applied in the mould for a gelcoat, or to a prepared substrate for flexible coatings, dried and cured. As a result, coatings are often prone to a number of defects including blistering, alligatoring, cracking, wrinkling, and many others [57]. Surface contamination, for example dust particles, can also lead to defects [58]. The application procedure becomes significantly more challenging when repair coatings are applied in the field, where the operator applies the coating suspended from a rope and the environmental conditions are less controlled. Defects created from either manufacturing or poor handling in the system can act as an initiation point for erosion [2], and severely decrease the lifetime of the coating.

Defects affect the ability of wind farm operators to accurately predict the lifetime of the protection systems [56]. This makes it difficult to schedule necessary repairs in advance and prevent further blade damage and turbine downtime.

Computational modelling is likely to play a part in the development of new and improved coatings as researchers aim to combine multistep models to provide a holistic model for leading edge rain erosion [59]. A number of analytical models have been developed that attempt to estimate the expected erosion lifetime of the protection system, where the lifetime is defined as the time it takes for the protection system to become undesirably rough and leave the incubation period [42,56,60–62]. Many analytical models, where not probabilistic, assume a perfect bond between the coating and the substrate. However, as stated, there are likely to be microstructural defects, such as voids, blisters and areas with a lack of adhesion. These change the local acoustic impedance causing the shock waves to be reflected wherever the defects occur. These shock waves reflect repeatedly through the coating and substrate structure until dampened out by the properties of the materials [45]. Defects are therefore stress raisers and become initiation points for further erosion. This aligns with research from Slot [56] who concluded that in order to increase the erosion performance of coatings, surfaces without defects and impurities need to be developed.

Defects such as voids in the composite blade structure also have the same effect. Discontinuities in the substrate reflect shock waves back into the protection system, which further load the material, thus increasing the rate of erosion damage and can eventually lead to

delamination [63].

Automating the application of protective coatings has the potential to reduce the number of defects in the coating. Robots traversing the full length of the blade in a single step could ensure a consistent finish across the blade surface [64]. However, implementing robots in the manufacturing process requires substantial investment, and an economic trade-off between the cost of automation, and the cost of additional repairs and reduced power production due to poorly applied coatings should be made.

Although modelling has a significant potential to increase understanding of blade erosion and failure mechanisms in the materials, modelling is currently only able to be developed on observed effects. Measurement of material property changes is currently not available during rain erosion testing, and measurement outside of the rain erosion test rig environment of material property changes is limited by the strain rate capability of analysis equipment. Current models predict that rain impact induces strain rates of 10^6 to 10^9 in the coating systems, however, current analysis equipment, such as Dynamic Mechanical Analysis, is limited to measurements at 10^4 , with extrapolation used to predict higher material strain rate values.

Erosion sensors currently in development, measuring material property changes in real time during the rain erosion test environment, offer an opportunity to further extend the knowledge of rain erosion degradation processes throughout the test lifetime, and to validate the computational models [65]. Initial trials show that creep occurs in the coating systems even in a dry environment at rotational tip speeds of 95 m/s, whilst creep occurs at much lower tip speeds of 25 m/s under rain droplet impact.

5.1.2. The effect of poor adhesion

Strong adhesion between the coating and the blade is necessary for mechanical performance. However, the adhesion also has a significant impact on the erosion performance of the system, with poor adhesion cited as the most obvious reason for an unsuccessful coating [66]. Poor adhesion can be caused by porosity or delamination at the coating-substrate interface.

Further investigation from Cortés [67,68] looked at the effect of adhesion on the rain erosion performance of flexible coatings. Two setups were compared; the first consisted of a filler applied to a biaxial laminate, with a flexible coating applied over it, and the second

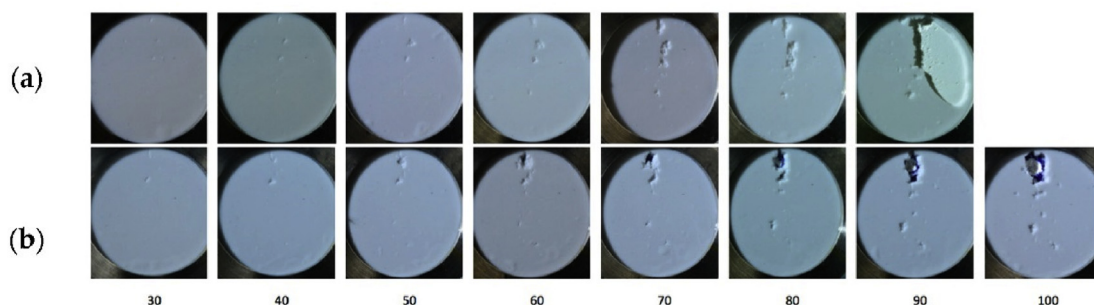


Fig. 7. Rain erosion testing results for flexible coatings a) without a primer layer and b) with a primer layer. Reprinted from Ref. [67] with permission.

included a primer layer between the filler and the coating to aid adhesion. The mechanical testing found that the inclusion of a primer significantly improved the adhesion of the coating to the filler. Subsequent rain erosion testing found similar incubation times for each setup. However, Fig. 7a shows that delamination occurs only in the first configuration causing a large section of the coating to be removed.

The results from Cortés demonstrate the importance of achieving a strong adhesive bond between the coating and the substrate. The low impedance of the coating transmits the impact stress and causes the first setup to fail at the interface due to its worse adhesion. This is illustrated by the severe delamination. The inclusion of a primer layer improves the adhesion, preventing failure at the interface, and moves the failure mode back into the coating as demonstrated by pitting in Fig. 7b. The results of the studies prompted Cortés to conclude that the adhesion of the coating to the substrate is of paramount importance to the rain erosion resistance of the system.

The final samples of a rain erosion test on flexible coatings performed by ORE Catapult can be seen in Fig. 8. There is a clear difference in the performance of samples 1 and 2, which experienced the removal of large areas of coating compared to sample 3, which experienced various levels of pitting. It is suspected that samples 1 and 2 performed significantly worse due to poor adhesion, evidenced by red areas

(Fig. 8b and c) showing early debonding and therefore allowing large strips of coating to be removed easily.

ORE Catapult uses aerodynamic profiles in its whirling arm erosion test rig. Aerodynamic profiles can make it challenging to apply coatings to the substrate, and so coatings can be prone to fail early if application cannot be performed effectively. However, the stark contrast in performance between samples 1 and 2, and sample 3 highlight the effect of poor adhesion on the rain erosion properties of flexible coatings.

5.2. Leading edge tapes

An alternative protection method to coatings is the post-mould application of highly flexible tapes, typically polyurethane, to the leading edge of the blade. Similarly to flexible coatings, **leading edge tapes** have a low impedance and are ductile to dampen the initial impact of the raindrops through deformation.

5.2.1. The effect of defects

As shown in the above section, the reduction of defects is key to the lifetime of a protection solution. Leading edge tapes are manufactured autonomously in a controlled environment away from the workshop where humidity and human interference may impact quality. This

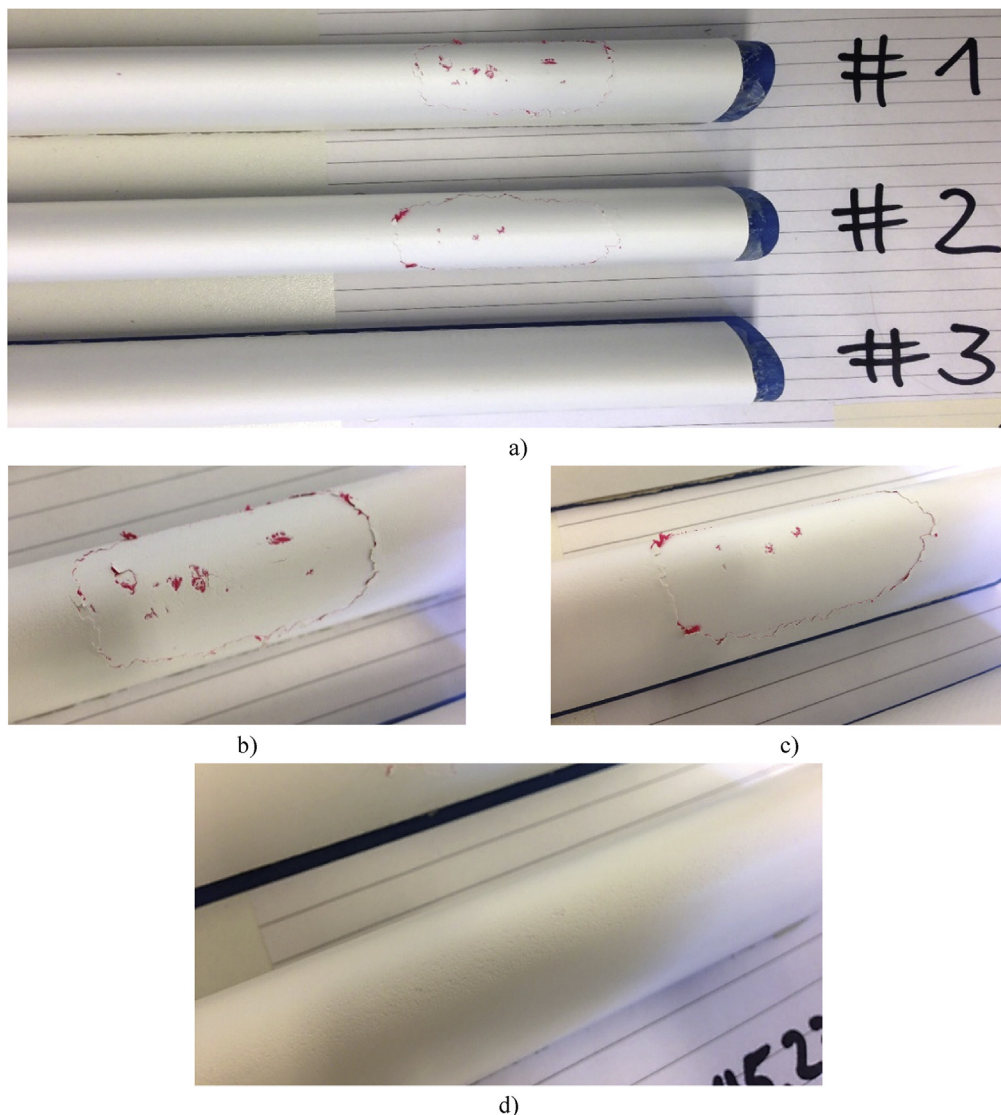


Fig. 8. a) Results of flexible coatings rain erosion performance: b) sample 1 exhibited large areas of debonding, c) sample 2 also exhibited large areas of debonding, d) sample 3 exhibited pitting and surface degradation.

reduces batch variability and, importantly, minimises the number of defects in the protection solution. Furthermore, leading edge tapes provide a consistent solution with a uniform thickness and finish. The high quality and reliability offered by tapes is challenging to achieve with protective coatings. Additionally, unlike chemical coatings, application of a tape is not affected by the weather conditions and so is believed to be a more reliable remedial solution to apply for in-field repairs [69].

5.2.2. The effect of poor adhesion

Applying a leading edge tape is an intensive process with a reliance on manual procedures [70]. The applicator is required to ensure a smooth surface, avoid wrinkles and tenting when the tape is applied, cut sections to size, seal and in some scenarios create splices if the tape is shorter in length than the blade area. It is also recommended that the edge sealer is used to protect the tape edges. This involved process risks the introduction of human errors, such as trapped air bubbles and areas of poor adhesion, and it is even more challenging in-situ. A small loss in adhesion in one area can cause the tape to disbond along the entire length of the blade [71].

Rain erosion testing on an industrial leading edge tape was performed by ORE Catapult. As with the previous ORE Catapult tests, three samples were used. Inspection of the samples prior to testing revealed several air bubbles across the whole surface area of samples 1 and 3, whilst sample 2 was firmly attached. Inspection every hour revealed that the trapped air bubbles acted as pressure points and cut through the tape, allowing water to enter and become entrapped underneath the tape (Fig. 9). The trapped water then caused severe tape detachment and the samples failed. Samples 1 and 3 failed after 8 h and 5 h, respectively. The well attached sample 2 failed after 11 h. The failure mode for sample 2 was surface damage, again demonstrating that strong adhesion moves the failure mode from the bond back into the protection solution.

Whilst the initial inspection was qualitative, the testing highlights the importance of achieving a robust bond with minimal air bubbles between the tape and the substrate to reduce the risk of tape disbond.

A study by Valaker [72] performed rain erosion tests on various protection solutions to determine impact mechanisms and important parameters. The study applied the respective protection solution to aluminium samples and subjected them to a whirling arm erosion test. The adhesion between the aluminium sample and the protective tape failed before any erosion was observed. Further experiments were conducted with additional binding elements in an attempt to aid adhesion of the tape but are not included in the publication. It is therefore possible to believe that these had minimal effect in alleviating the issue. Valaker noted that the controlled production method of the tapes makes it probable that they do possess good erosion resistance and that if strong adhesion can be secured then the erosion resistance can be expected to exceed that of coatings.

The research presented aligns with the work from Keegan who concluded that the bond strength between the tape and the substrate is critical to the performance of the tape. Increasing the adhesion of the tape, through adhesion promoters and other methods, reduces the risk of the tape disbonding, but increases the challenge of application as the

correction of wrinkles and other mistakes becomes more difficult, leaving less room for human error. The presented studies already show that the erosion resistance of leading edge tapes is often not being utilised due to difficulty of application. Future developments in automating the application of leading edge tapes through robots may provide the breakthrough in achieving consistent robust bonds and allow for the potential of leading edge tapes to be realised.

5.2.3. Effect on aerodynamics

The automated manufacture of leading edge tapes allows them to have a greater thickness than coatings without introducing additional defects. This thicker layer helps to expand the shockwave resulting in a lower pressure in the protection system and blade substrate. It also has the advantage of effectively moving any defects or voids in the blade substrate itself further from the incoming and dissipating stress wave. Tapes are typically 0.3 mm thick [70], and therefore protrude from the leading edge.

Keegan presents research from Chinmay [73], which found that, depending on size and position, implementing tapes on aerofoils results in an increase in drag between 5 and 15%. Chinmay concluded that, although this may not result in a measurable difference in AEP, research is required to determine the optimum method of application to minimise any power losses. Further research from Kidder [74] explored the use of tape on a full scale commercial turbine tip. Kidder found that the aerodynamic performance impact of the tape was significant at low angles of attack, measuring 20% drag and up to 25% loss in lift. However, the impact to drag and lift subsided at high angles of attack.

Chinmay and Kidder both present losses in aerodynamic performance, although these are not alarming. However, the effect of the slightly unfavourable aerodynamics on the turbine loading and fatigue are unclear. The use of thinner tapes would alleviate these potential issues, but this is likely to defeat its original purpose [75]. The minimal losses in performance is likely offset by the protection provided by a well applied tape.

5.3. Erosion shields

A recent development in protection solutions is applying highly durable covers to the leading edge in modules. These will be henceforth be referred to as **erosion shields**. As with leading edge tapes, erosion shields are manufactured in controlled production environments, minimising the number of defects.

Erosion shields are either rigid or semi-flexible and are affixed in a single piece, or shorter dovetailed pieces, using adhesives. This avoids wrinkling issues during the application process that can be common with tapes. Erosion shields also tend to be thicker, thereby further expanding and dissipating the raindrop shock wave than tapes or coatings, reducing the transfer damage to the rigid composite blade. The greater thickness also serves to move any voids in the blade substrate further from the shock waves.

However, differences in flexibility and rigidity may cause high interfacial stresses between the blade and shield during blade operation. In severe cases this could lead to the adhesive breakdown and the shields disbonding from the blade.



Fig. 9. Significant tape detachment and water entrapment in sample 1 after 8 h (left) and in sample 3 after 5 h (right) of rain erosion testing.

As erosion shields are manufactured ready to be positioned straight onto the leading edge, they can have their shape tailored for specific blades. This ensures a near perfect fit and results in only marginal modifications to the geometry of the blade. This makes erosion shields initially more expensive, however, should it alleviate the effect of leading edge erosion, they could represent a better return on investment to turbine owners. This will become apparent as the technology develops and becomes widely utilised.

An example of an erosion shield is *armourEDGE* [76]. The shield is manufactured from extruded sheets of a tough thermoplastic. When some thermoplastic materials erode, they do not result in large pits but instead provide a smooth removal of the material, providing a more preferable aerodynamic performance. The extruded thermoplastic is then thermoformed into the desired shape and the edges of the shield are tapered to provide a smooth transition between the blade and shield [77]. The shields are adhesively bonded in place and it is recommended that a protective coating be used to protect the joints. It is suspected that the reliance on the adhesive in this solution is high, and that care must be taken to ensure a robust bond to avoid the shield disbonding from the blade.

ELLE from PolyTech [78] applies a robust polyurethane softshell to the exterior blade leading edge in a similar manner to tapes. Self-adhesive strips are applied to the ELLE material on production, with the adhesive matched to the existing blade substrate. The protective film from these strips is removed during application, allowing a wide weather window for the application process. After consolidating the adhesive bond, the edges of the ELLE shield are sealed. Unlike tapes however, the thickness of the solution is not uniform, with material thickness at the leading edge being up to 6 mm which tapers down to low thicknesses for the sealed edges. Performance of the product in rain erosion testing has been high, with no erosion being visible after 100 h of testing [78]. The product has also been tested on a demonstration wind turbine for three years with no loss of adhesion or erosion so far.

Erosion shields have been employed for a number of years in the helicopter industry [79] with one of the leading suppliers being Doncasters Limited. Similarities between the rain erosion experienced by helicopter blades and wind turbine blades enable comparisons between respective protective systems. Weigel [80] identified that polyurethane materials, which are typically used as flexible coatings and leading edge tapes, were outperformed in rain erosion tests by metals. As a result, metallic shields, typically composed of stainless steel, nickel or titanium, are bonded to helicopter blade leading edges as the rain erosion protection system [81]. Although the shields have outstanding rain erosion resistance, maintaining adhesion in service can be an issue, with regular inspections being performed of the bonded shields during aircraft checks. Whilst shield replacement can be performed on aircraft during maintenance, replacement of solid shields in-situ on wind turbine blades is difficult, especially with respect to high performance of the repair adhesive bond.

Metals have substantially higher impedances than typical gelcoats [56]. Therefore, upon droplet impingement the metal reflects a large proportion of the droplet impact energy, resulting in high energy jetting across the surface. However, a smooth surface and a high hardness that resists plastic deformation mitigates the damaging nature of the jetting. The dominant damage form of metals is still surface degradation. The high impedance ensures a smaller proportion of droplet energy is transferred and subsurface degradation and damaging of the bond is reduced. This resistance allows certain metallic shields to have excellent rain erosion performance at higher tip speeds than seen for polymeric materials. Fig. 10 presents rain erosion tests on a nickel alloy sample, showing no surface degradation after 85 h at rotational speeds of 173 m/s, estimated to give a 30 + year lifetime on wind turbine blades operating at tip speeds of 120 m/s.

If metallic erosion shields can be effectively attached to a blade leading edge, they then offer potential to prevent leading edge erosion and allow future blade designs to operate at higher tip speeds.

Doncasters Limited, in association with various UK partners, are currently developing an attachment solution. If successful, the new solution is estimated to reduce the LCOE by 3.2%. ORE Catapult is also considering adhesively bonding the metallic shield to the leading edge of the Levenmouth 7 MW turbine for further demonstration of erosion resistance at 95 m/s tip speeds.

5.4. Integrated erosion shield

Co-bonding or co-curing a shield directly into the blade mould during manufacture offers an alternative to adhesively bonding the shield to the leading edge. This would integrate and countersink the shield into the blade in an in-mould manufacturing step, providing a lifetime rain erosion solution for production blades at high tip speeds whilst reducing the additional manufacturing steps required for current leading edge coatings and tapes.

In the co-bonding technique, the same curing cycle is used to cure the adhesive and the composite and as a result the additional post cure thermal stresses are not experienced by the composite. Co-bonding also has the advantages of only requiring surface preparation of the shield and only forms a mechanical bond between the adhesive and the metal [82]. The bond between the adhesive and the uncured composite is characterised by chemical reactions occurring between the adhesive and the matrix material of the composite. A strong chemical bond is therefore formed. However, there are two distinct interfaces, a mechanical bond between the shield and adhesive and a chemical bond between the adhesive and composite matrix, and therefore care must be taken to ensure a suitable adhesive is chosen to form robust bonds with both the shield and composite [83].

Co-curing involves curing the composite directly onto the shield, forming a mechanical bond between the shield and the matrix system of the composite. The excess resin, extracted during consolidation of the composite, provides the adhesion between the shield and the composite [84]. This has the advantage of removing the adhesive from the bond. Similar to co-bonding, care must be taken to ensure a suitable resin is chosen to ensure consolidation of the composite and a robust bond with the shield.

Combining the attachment of the shield into the curing of the blade itself would require only one mechanical bond between the shield integration, as opposed to two in post-mould adhesive bonding. The process would also negate both the need for and time required of an additional manufacturing step, as well as ensuring a smooth exterior to the blade, with no step in the profile where the shield is included.

6. Conclusions

The offshore wind industry has experienced a rapid growth in the last ten years and appears set to play a large role in the world's pursuit of sustainable, clean energy. During this time, the size of offshore wind turbines has soared towards 12 MW and tip speeds have reached approximately 100 m/s. New markets in the US and Asia have developed,

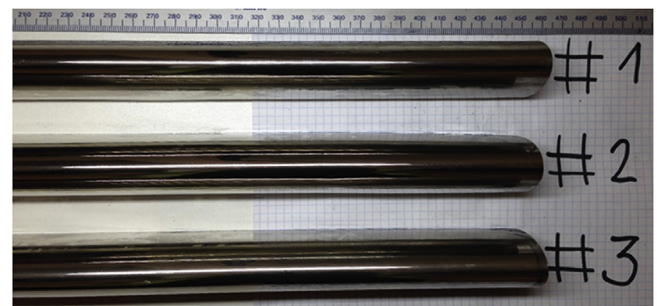


Fig. 10. A nickel alloy sample after 85 h of rain erosion testing at a rotational speed of 173 m/s.

Table 1
A simplified summary of existing protection solutions.

Protection Solution	Application	Susceptible to defects	Susceptible to poor adhesion	Aerodynamic issues	Debonding risk due to stiffness mismatch	Type average erosion resistance
Gelcoats	In-mould	Yes	No	No	No	Poor
Flexible Coatings	Post-mould	Yes	Yes	No	Yes	Medium
Leading Edge Tapes	Post-mould	No	Yes	Slightly	Yes	Good
Erosion Shields	Post-mould	No	Potentially	Potentially	Yes	Very good
Integrated Erosion Shields	In-mould	No	No	No	Yes	Excellent

with the monsoon seasons expected to pose a significant threat to wind turbines in Asia.

Since 2013, the prominence of leading edge erosion has grown from a small number of anecdotal cases occurring only in the most extreme environments, to causing almost entire wind farms in relatively moderate environments to require emergency repairs and has subsequently developed into one of the industry's most significant concerns. Quantifying precisely the negative effects of the problem is challenging, with research differing on the reduction in the AEP. However, there is clear consensus that leading edge erosion does negatively affect AEP and can do so within a few years, therefore requiring expensive repairs and tip speeds to be limited to protect blade edges. As a result, several protection solutions have been developed to attempt to mitigate and slow the onset of leading edge erosion.

Existing protection solutions have been presented and discussed in an attempt to understand their advantages and disadvantages. Table 1 provides a summary of the solutions. There appears to be several common failure themes including poor adhesion prompting early detaching, as well as poor manufacturing and application techniques that introduce defects and hence initiation points for erosion.

Coatings, both gelcoats and flexible coatings, rely heavily on intensive manual procedures to produce and apply to the blade, regardless of whether application is in-mould or post-mould. This leaves coatings vulnerable to defects that negatively affect their erosion performance. Leading edge tapes are manufactured autonomously in a controlled environment and are consequently relatively free of defects. However, if not effectively applied, wrinkles and air pockets can be introduced that reduce the adhesion of the bond. The low impedance of the leading edge tape, whilst effective at absorbing the energy of the impacting raindrops, fails through subsurface degradation that can eventually cause the tape to disbond, with this greatly accelerated in areas of poor adhesion.

Erosion shields, and particularly metallic erosion shields, have the potential to overcome a lot of these issues. Like tapes, shields are also manufactured autonomously in a controlled environment to reduce defects. However, they can be effectively tailored to specific blades to minimise discontinuities and ensure a good fit, whilst their greater rigidity removes the risks of wrinkling occurring. Metallic erosion shields have been shown in both the helicopter industry and in rain erosion tests to exhibit excellent erosion resistance. Furthermore, their high impedance ensures that any erosion occurring is likely to be seen at the surface, reducing the reliance on the adhesive. However, the long term adhesive performance remains in question, due to creep and structural loading.

Integrating a metallic erosion shield into the blade mould and co-curing or co-bonding it to the blade substrate removes an additional manufacturing step and allows the shield to sit flush with the blade, avoiding any aerodynamic issues. An integrated metallic erosion shield may then offer the solution to solving leading edge erosion if a design can be found that mitigates the differences in flexibility between the two components and eliminates the risk of the shield detaching and leaving the blade completely exposed.

In 2013, Keegan stated that there is no solution to leading edge erosion that can protect a wind turbine blade for its 25 year lifetime,

and that is currently still the case. However, now solving the issue of leading edge erosion is far more important than in 2013; with the offshore wind industry expected to continue its rapid expansion, wind turbines set to continue their growth in size and the emergence of new, more hostile markets. Consequently, there remains both a challenge and an opportunity to solve one of the most prominent problems facing the offshore wind industry.

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